

Anomaly Detection for Resilient Control Systems Using Fuzzy-Neural Data Fusion Engine

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Outline

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- Data Fusion Engine Architecture
 - Self-Organizing Map for Anomaly Detection
 - Artificial Neural Network for Signal Prediction
 - Fuzzy Logic based Alarm Generation
- Experimental Results
- Conclusion

Motivation

- Resilient control systems:
 - Task:
 - Implement robust cyber-secure environment
 - Ensure increased state-awareness.
 - Solution:
 - Complex system monitoring
 - Real-time system behavior analysis
 - Timely reporting of the system state to the responsible human operators

Hytest System

- Hytest Chemical Plant Model
 - Suitable test-bed for data-fusion system development
 - Matlab Simulink model of the INL's Hytest process
 - Testing facility for hybrid energy systems composed of tightly coupled chemical processes.
 - Interconnected modules, e.g. chemical reactors, heaters, condensers, storage tanks.
 - Over 140 sensory measurements to monitor

Data Fusion Engine Architecture

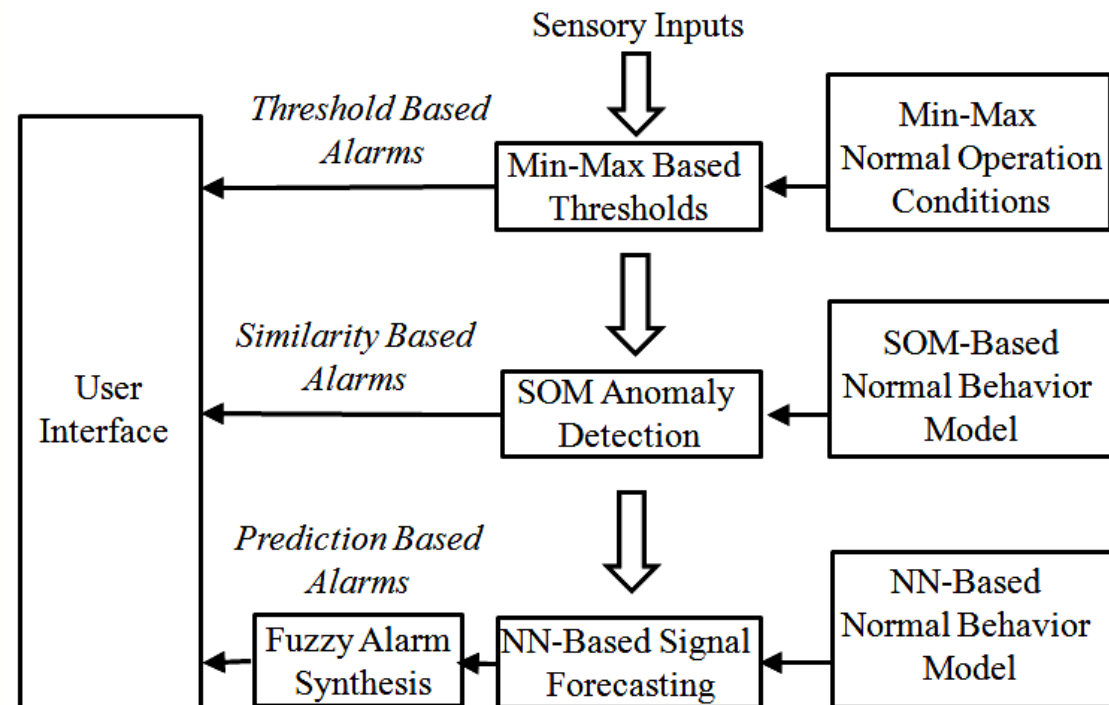
- Three-layered systems:
 - Conventional min-max bounds
 - SOM based similarity computation
 - Neural-network based signal prediction

HMI

On-line Processing

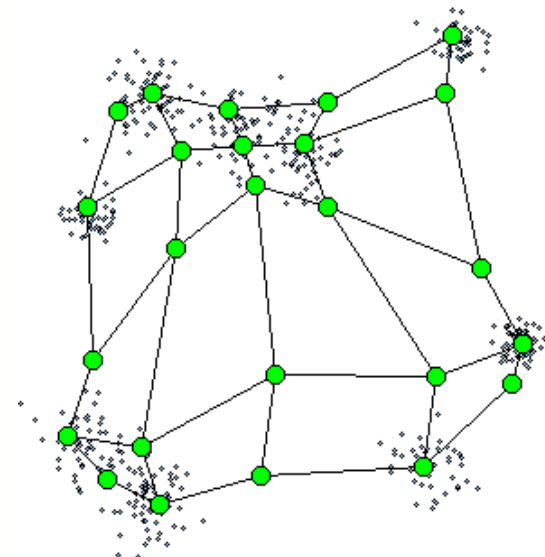
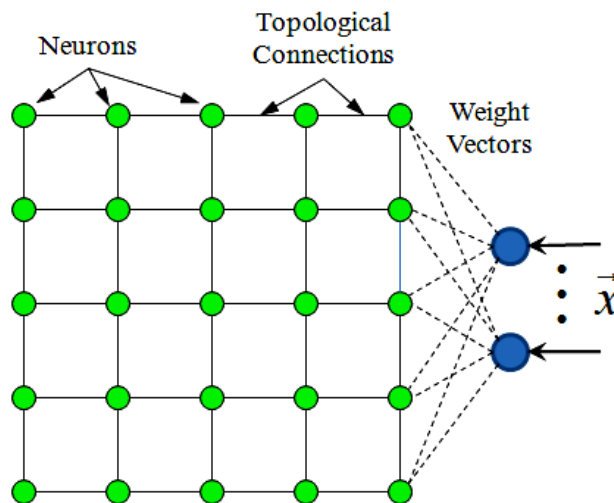
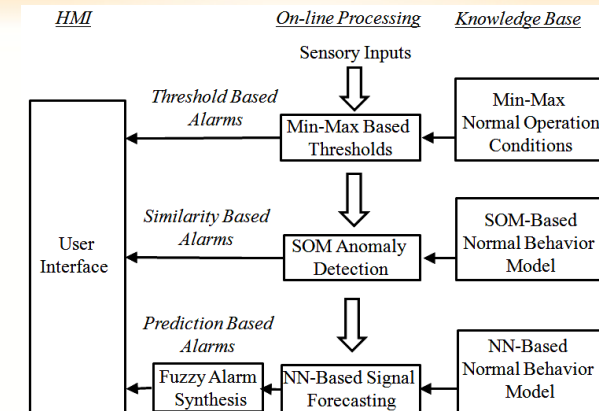
Knowledge Base

- Knowledge base
 - constructed offline
- Fuzzy Alarm Synthesis
 - combines multiple prediction alarms into a robust anomaly indicator



Self-Organizing Map (SOM) for Anomaly Detection

- Training on approved normal behavior
- Accurate modeling of multi-dimensional topology of the normal behavior (unlike the min-max bounds)
- Self-Organizing Map (1981)
 - Combines unsupervised winner-takes-all competitive learning with cooperative adaptation
 - 2D lattice of neuron position in a fixed grid

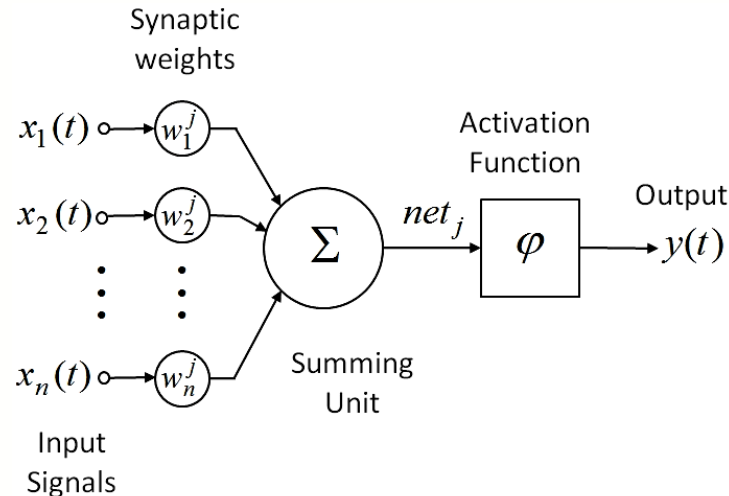
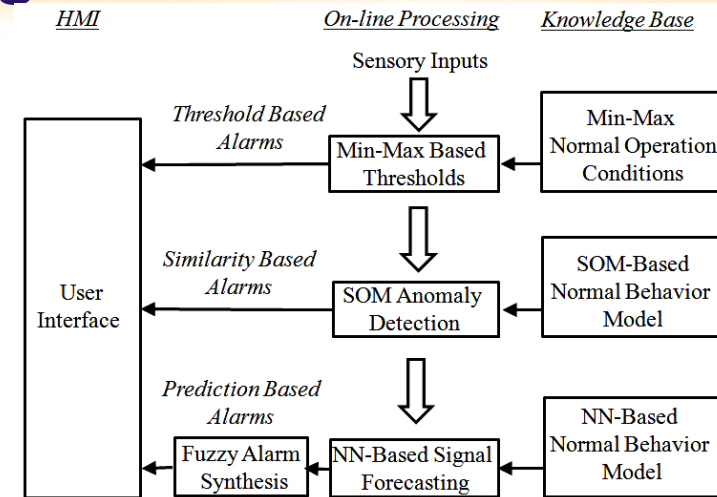


Self-Organizing Map for Anomaly Detection

- Training:
 - Input: current measurement, previous measurement and signal gradient
 - Learns the multi-dimensional topology of the input data
- Testing:
 - Each SOM neuron transformed into a fuzzy rule.
 - Each fuzzy rule describes the similarity of an input vector with normal behavior patterns.
 - Gaussian membership function for each fuzzy set
 - Mean at the position of the neuron
 - Spread based on topological neighborhood in the SOM.
 - The similarity output computed as the maximum firing strength of all fuzzy rules.

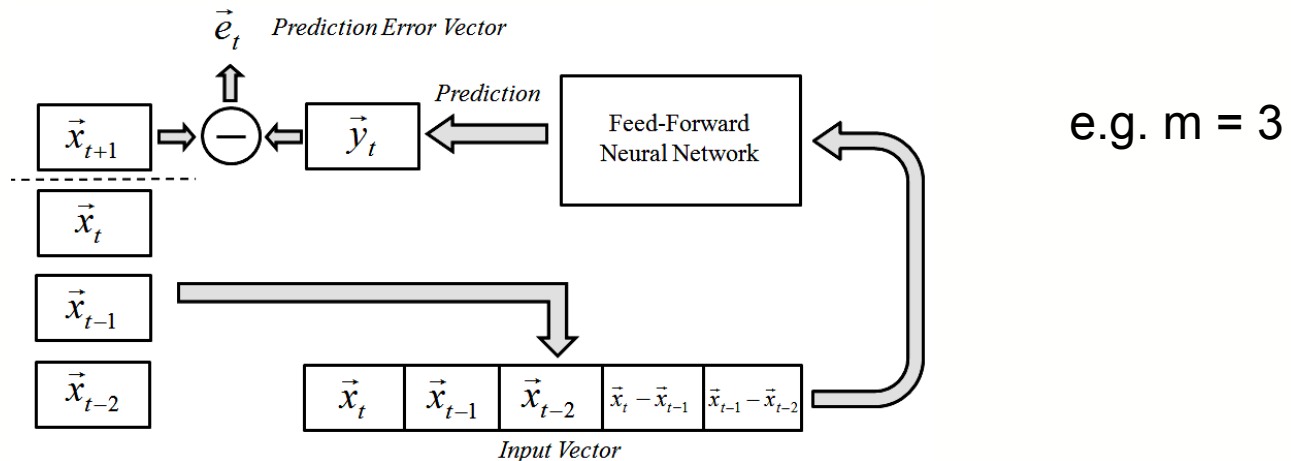
Artificial Neural Network for Signal Prediction

- Artificial Neural Network (ANN)
 - Predicts the near future behavior of the system
 - Feed-forward architecture composed of multiple interconnected neuron layers.
 - Uses supervised learning based on error-back propagation



Artificial Neural Network for Signal Prediction

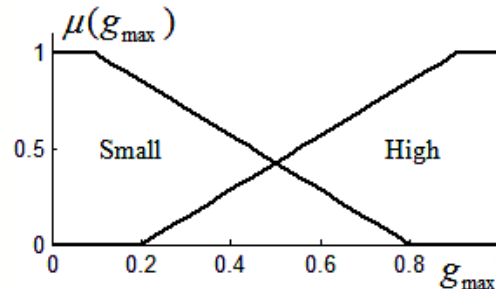
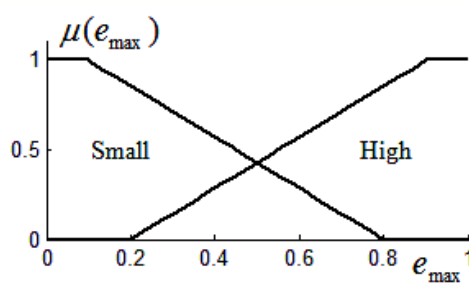
- Models the dynamics of the underlying physical processes
- Input vector constructed from m previous sensor measurements



- ANN predicts next k sensory measurements.
- The predicted measurements retrospectively compared to the real measurements
- Prediction error calculated for each sensor.

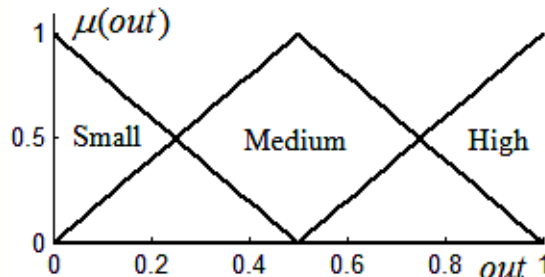
Fuzzy Logic based Alarm Generation

- For plant module with 9 sensor the ANN predictor produces 9 prediction errors.
- Fuzzy Logic System (FLS)
 - Fuses the alarms into a single robust anomaly indicator
 - Input: maximum prediction error and the gradient of the measurement.
 - Output: the anomaly indicator



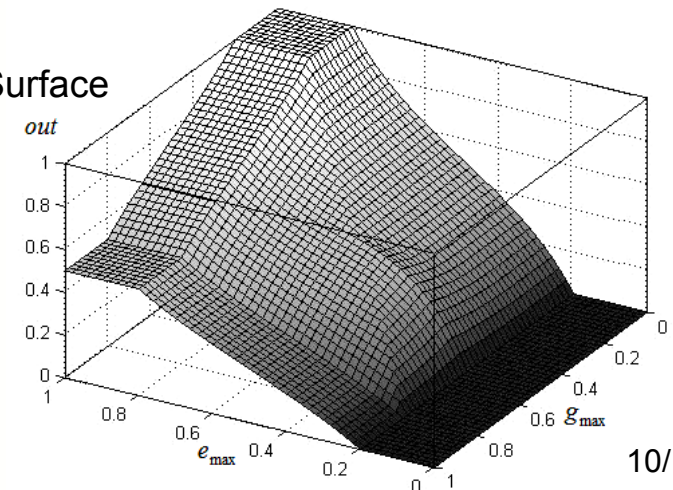
FUZZY RULE TABLE

e_{\max}/g_{\max}	<i>Small</i>	<i>High</i>
<i>Small</i>	<i>Small</i>	<i>Small</i>
<i>High</i>	<i>High</i>	<i>Medium</i>



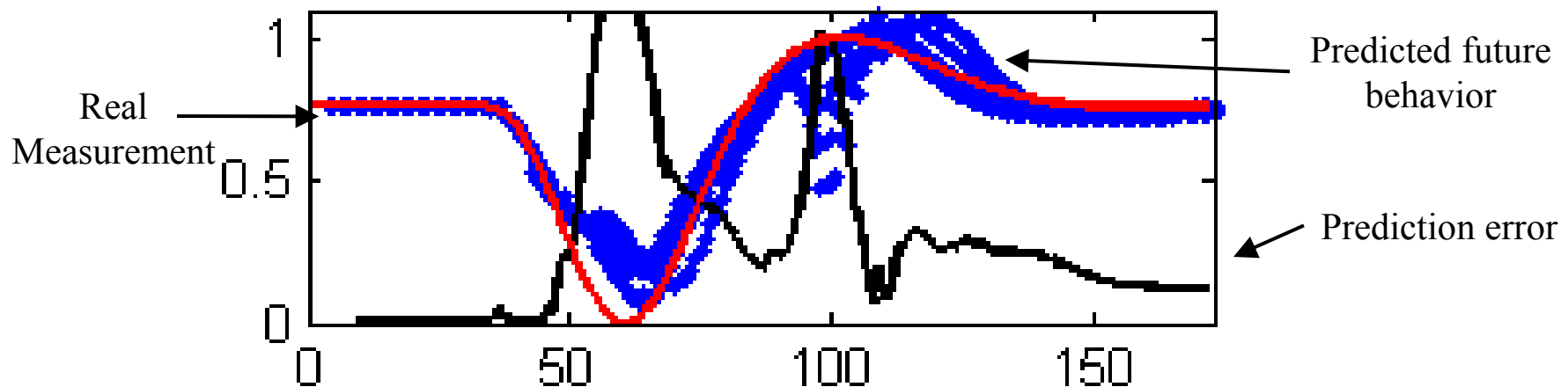
Higher prediction errors are expected during plant transients

Output Surface



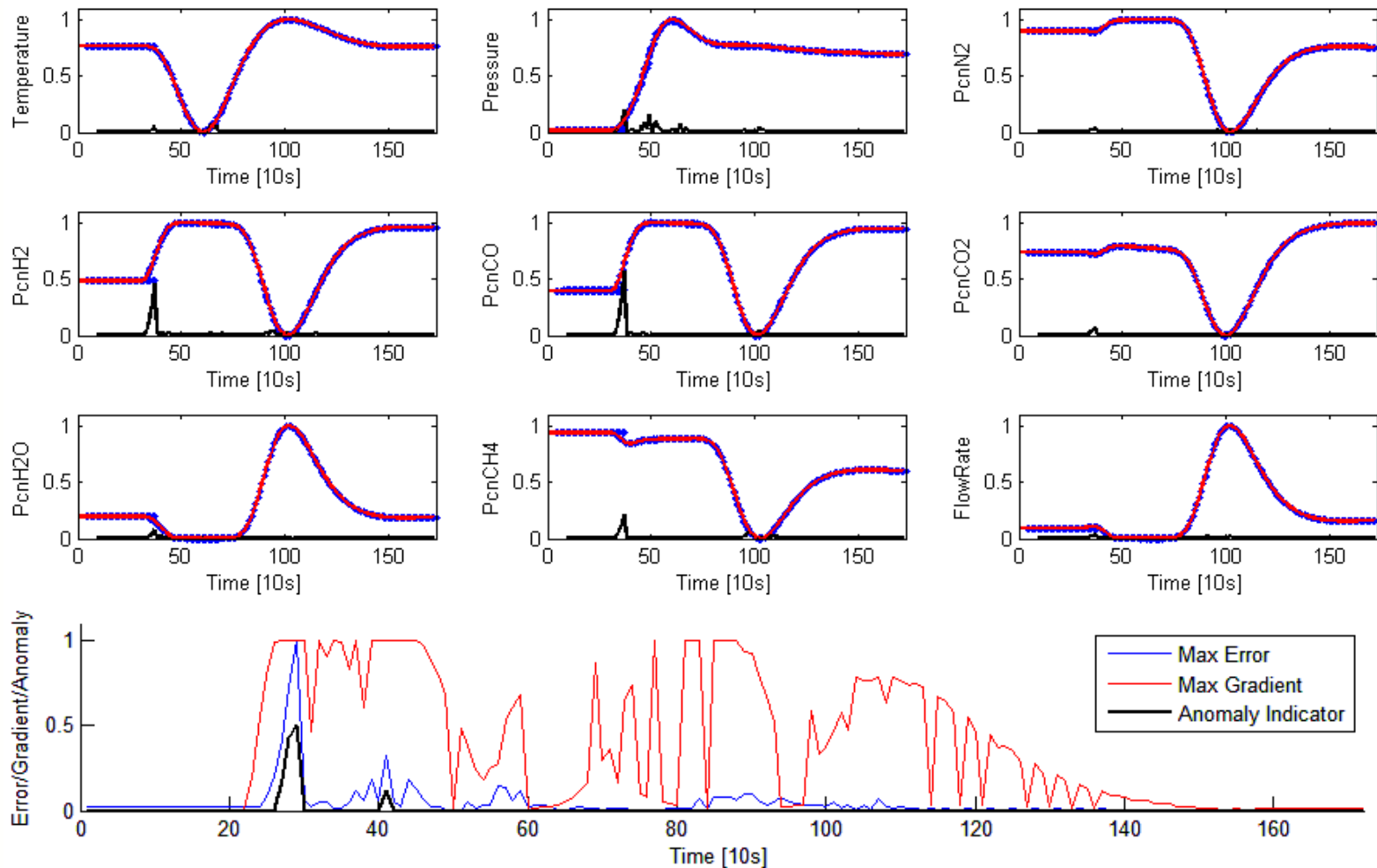
Experimental Results

- Focus on single component of Hytest
 - Chemical reactor
- Three considered experimental test cases:
 - Normal transient
 - Transient with component failure
 - Intrusion attempt



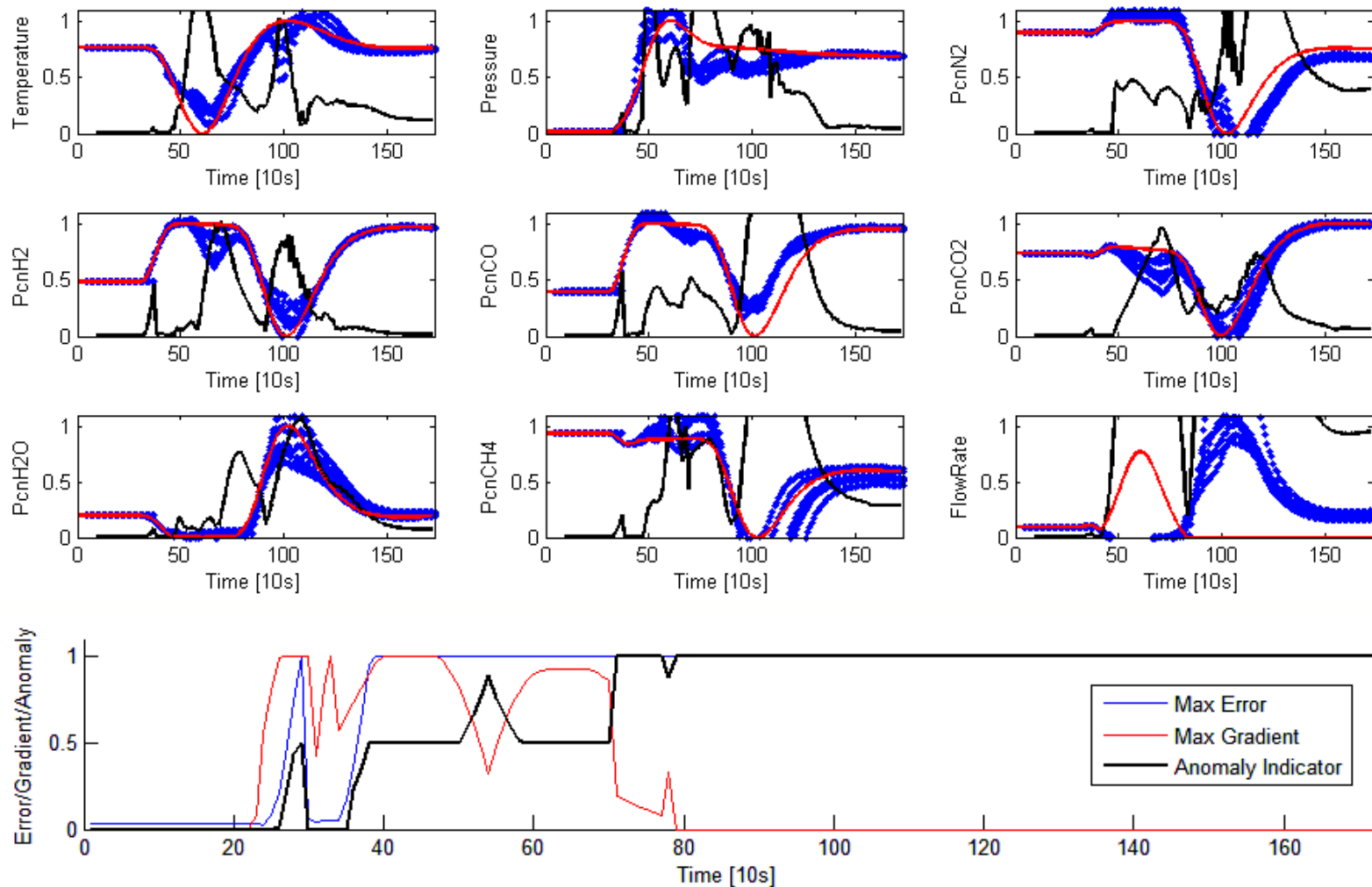
Experimental Results

- Normal transient



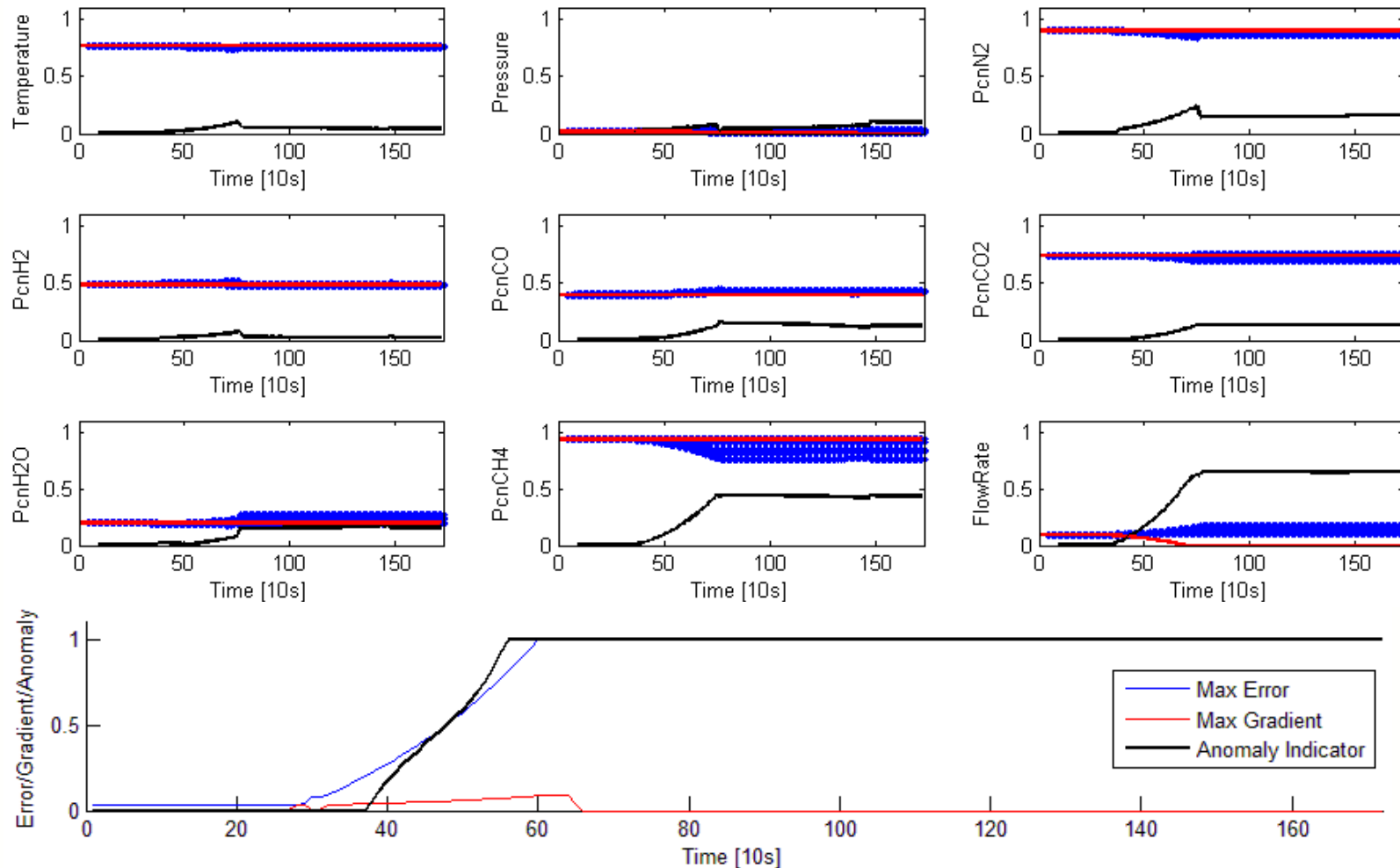
Experimental Results

- Transient with component failure



Experimental Results

- Intrusion attempt



Conclusion

- Developed Fuzzy-Neural Data Fusion Engine (DFE)
- Integrated the DFE with the Hytest chemical plant model
- It was demonstrated that the DFE improves the state-awareness of the Hytest plant operator
- The DFE successfully detected component failures as well intrusion attempts on the control system.
- Future work (currently ongoing research)
 - Implement threshold values for alarm generation
 - Further refinements of computational intelligence algorithms
 - Human factors evaluation of the performance

Acknowledgement

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